The Dodelson-Widrow mechanism & neutrino self-interactions

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Based on 1910.XXXX
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Why sterile neutrinos?

- Provides the SM neutrinos with the ‘right’ partner.

- Can give masses to neutrinos.

- Can be used to answer the baryon-asymmetry of the universe through leptogenesis.

- Possible dark matter candidate. Can also be used to solve small-scale structure problems.

- Hints in terrestrial experiments?

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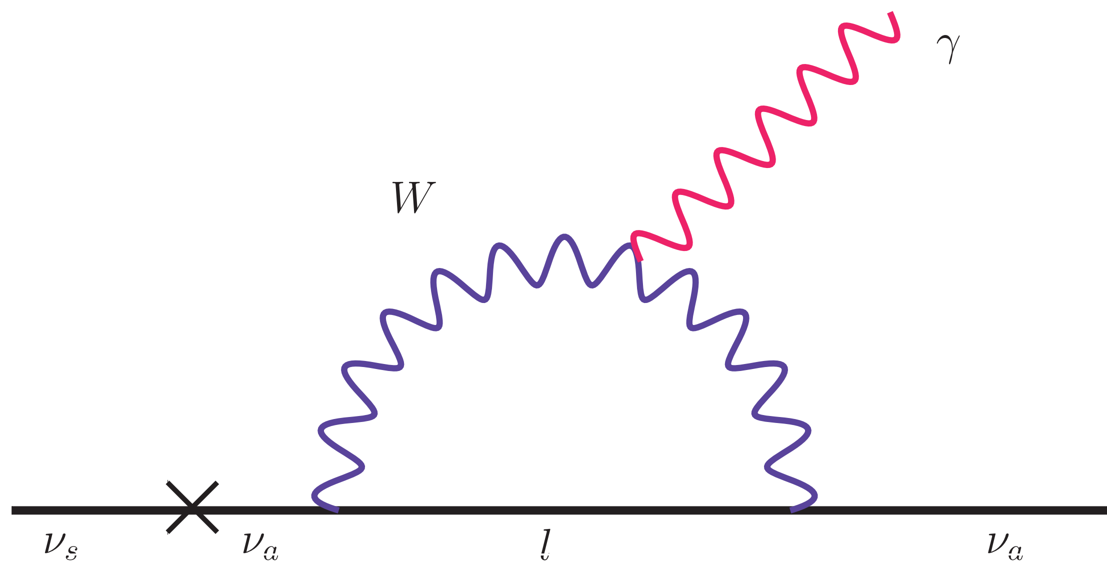
- Hints in terrestrial experiments?

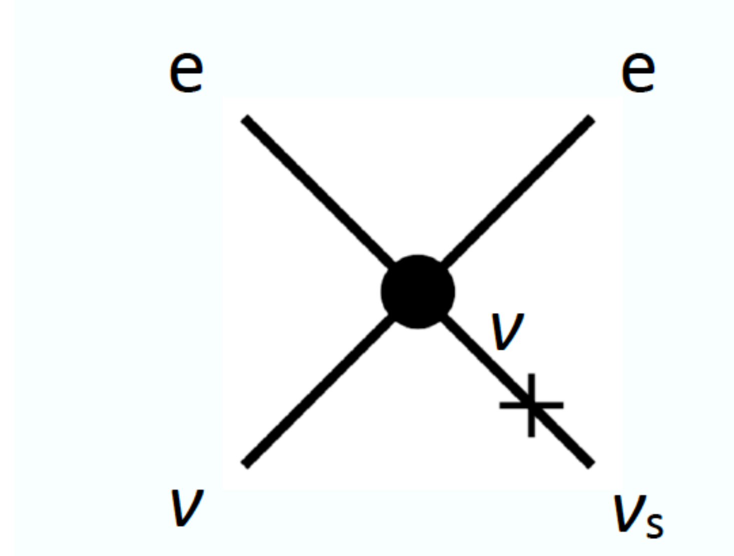
Sterile neutrinos as Dark Matter



- 4th mass eigenstate $\nu_4 = cos\theta\, \nu_s + sin\theta\, \nu_a$
- Phase space bounds hold, say $m_4 > \mathrm{keV}$.
  Tremaine and Gunn, PRL1979
- Can be detected through 1-loop decay into photons: $\nu_s \to \nu_a\gamma$.
- Decay rate $\Gamma \propto m_4^5 \sin^2 2\,\theta$. Pal and Wolfenstein , PRD1982
  Sharp X-ray line at $E_\gamma = m_4/2$.
- Non-observation puts bound on $m_4 - sin\,2\,\theta$ plane. (Hints of a line at $m_4 = 7.1\,\mathrm{keV}?-$ Bulbul et al. Astro. 2014)

Production: the Dodelson-Widrow mechanism

- The ν_s cannot be in thermal equilibrium with SM particles before BBN.



- Must be produced non-thermally with $\theta \ll 1$.

- ν_a oscillates into ν_s before decoupling. Creates a non-thermal population of ν_s.

Dodelson and Widrow, PRL1994

$$T\frac{\partial}{\partial T} f_{\nu_s}|_{p/T} = \frac{\Gamma_a}{2H}\langle P(\nu_a \to \nu_s)\rangle f_{\nu_a} \;,$$

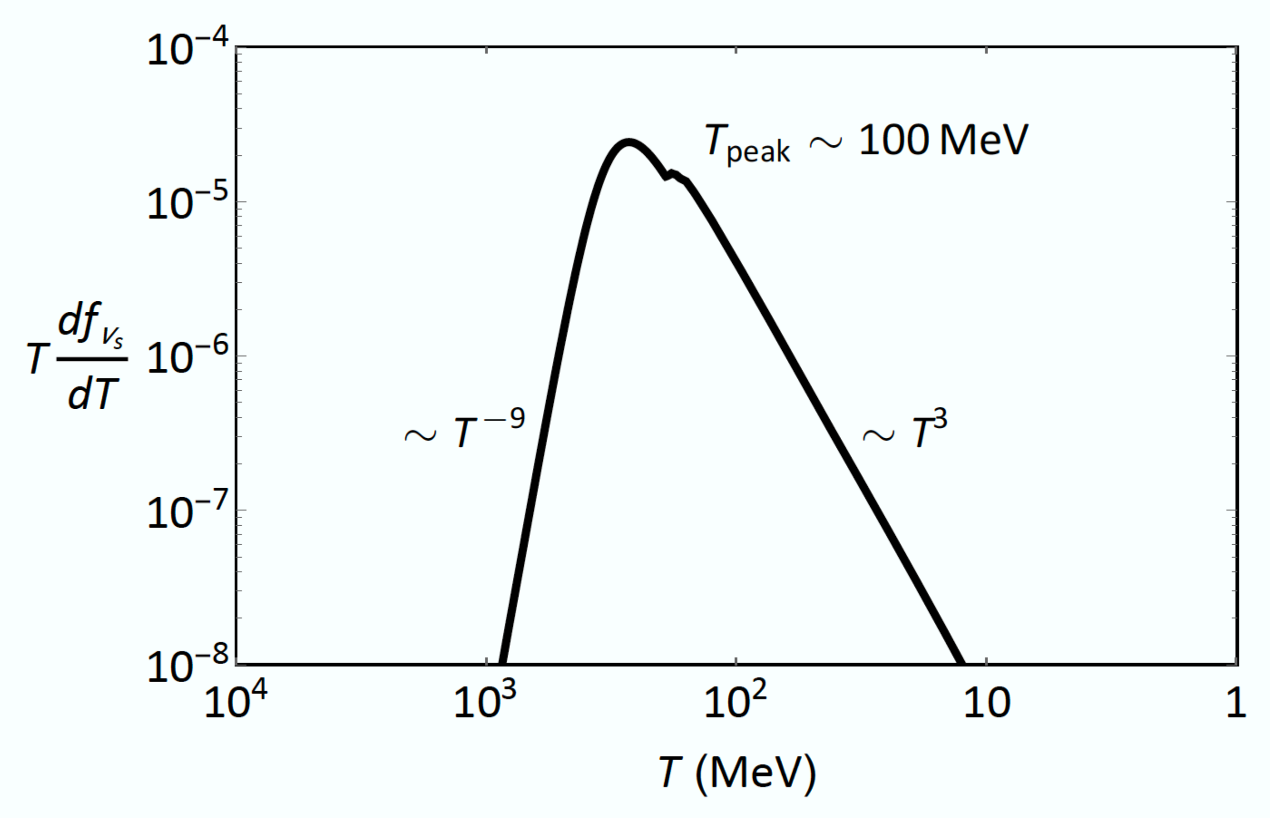
$$\langle P(\nu_a \to \nu_s)\rangle = \frac{1}{2}\frac{\Delta^2 sin^2 2\,\theta}{\Delta^2 sin^2 2\,\theta + \frac{\Gamma_a^2}{4} + (\Delta cos\, 2\,\theta - V)^2}$$

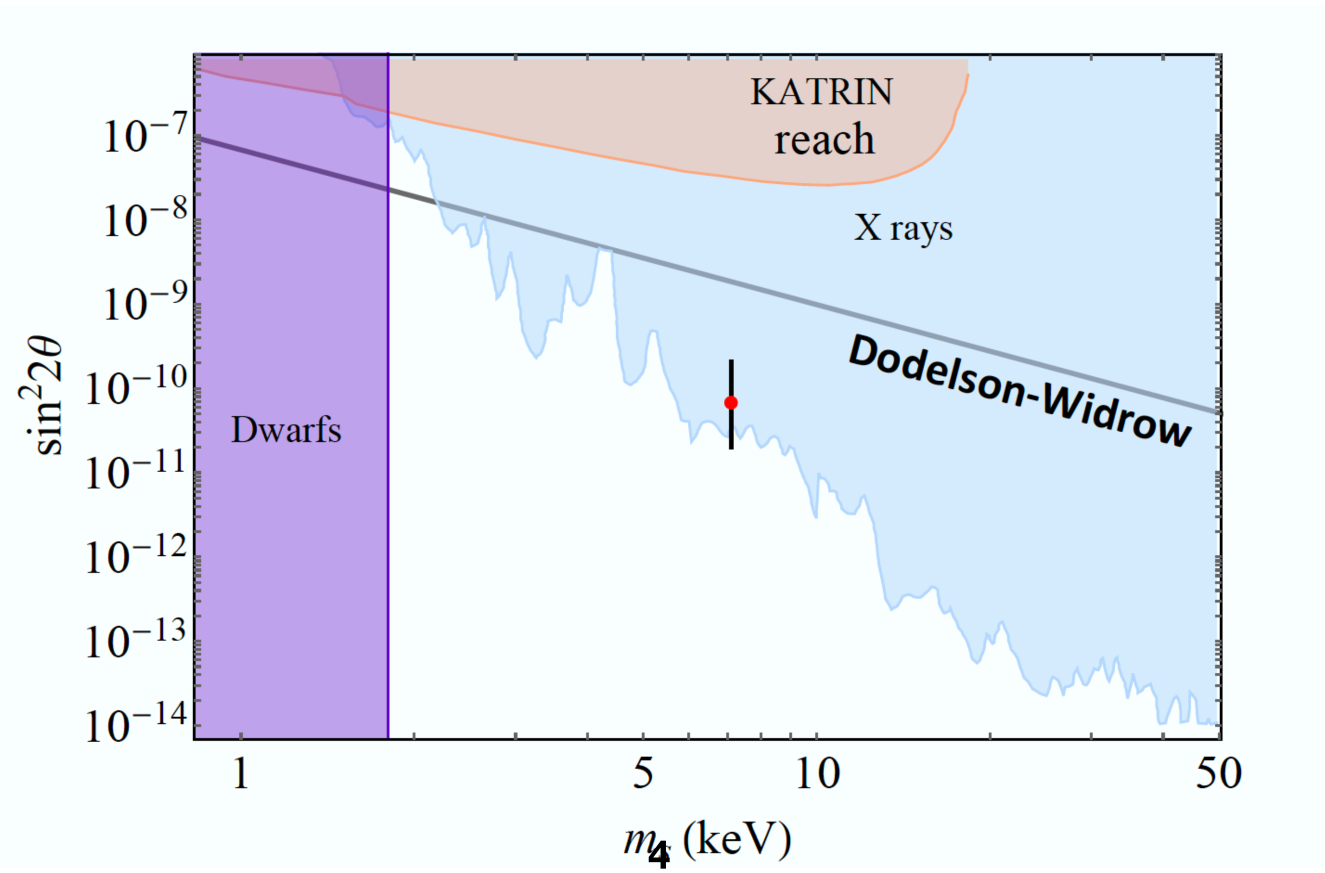
$\Delta = m_s^2/2E$

Quantum Zeno damping

Matter potential

The Dodelson-Widrow mechanism… contd





- ν_s freeze in. Production is maximized at T~100 MeV.
- Ruled out by X-ray bounds and phase-space considerations (Tremaine-Gunn, Lyman alpha, etc.).
- A finite lepton asymmetry (Shi-Fuller Mechanism) can help.

  Shi and Fuller, PRL 1999

  see Luke's talk!
- Can we open up parameter space without introducing a lepton asymmetry?

Self-Interacting neutrinos

- Note that relic ~ (rate X mixing angle). Increasing rate can satisfy same results for smaller θ.

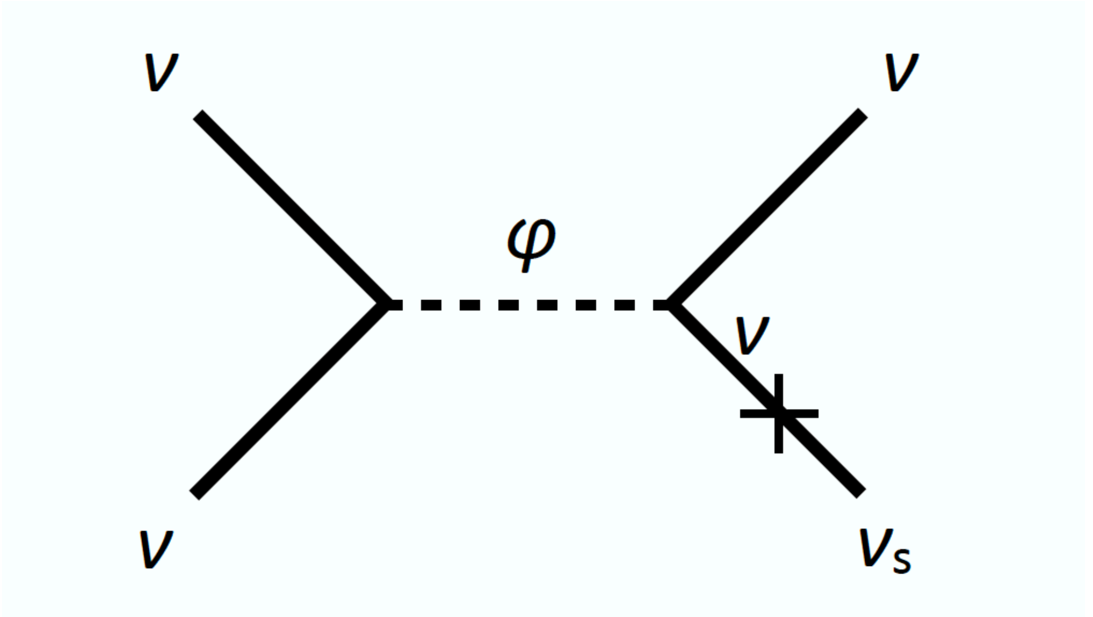
- Neutrino self-interactions. Recently proposed as a viable solution to the Hubble tension. Requires $G_{\rm eff} \gg G_F$.

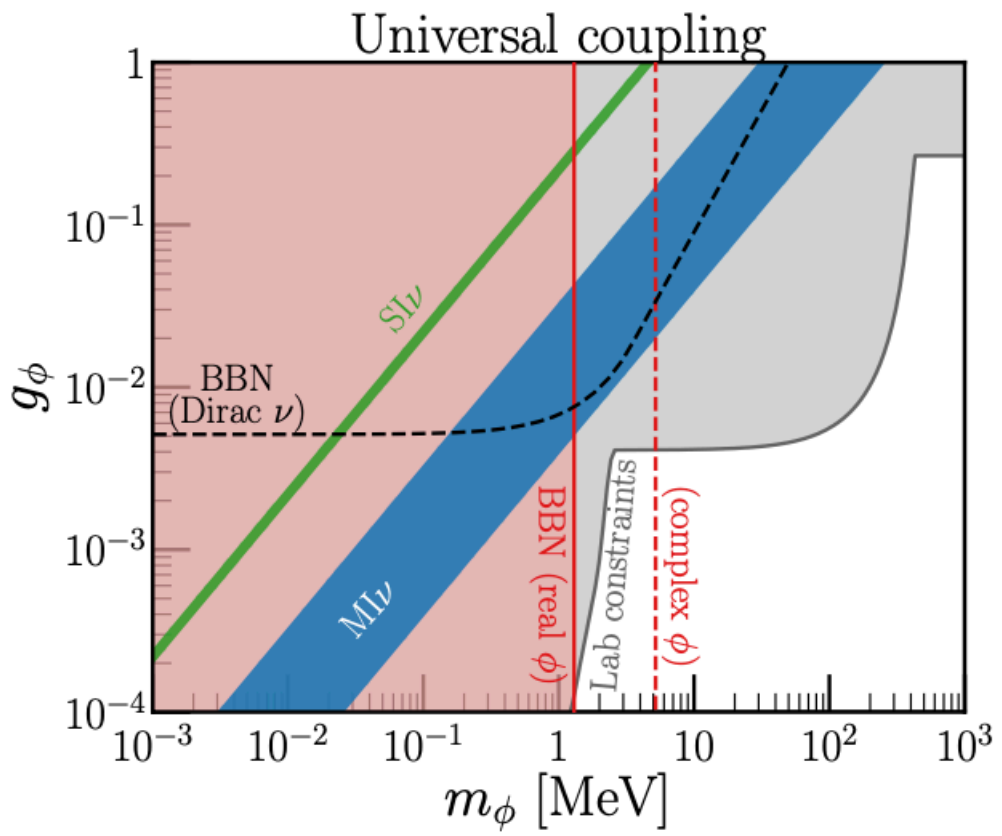
  Kreisch, Cyr-Racine and Dore, 1902.00534

- Consider

  $$\mathscr{L}_\nu = \frac{y}{\Lambda^2}(LH)^2\varphi \xrightarrow{\text{EWSB}} \lambda_\varphi \nu_a \nu_a \varphi,$$ where φ is a complex scalar. Can be heavy or light.

  Berryman, de Gouvêa, Kelly and Zhang PRD2018

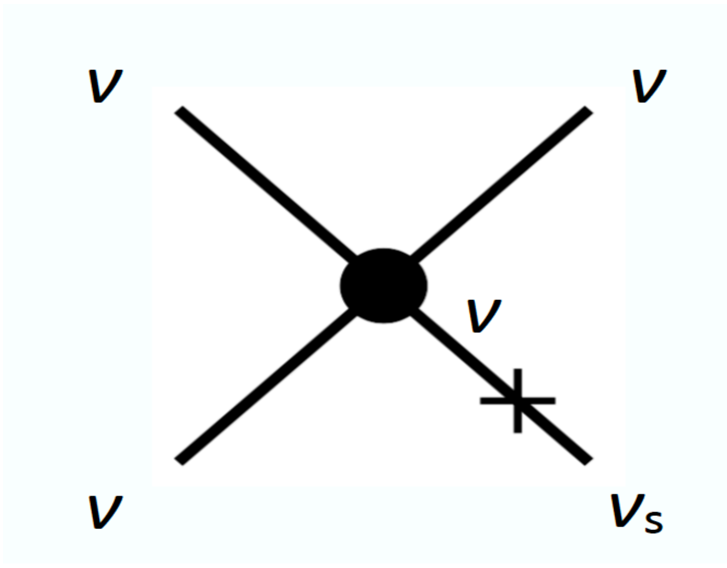




Blinov, Kelly, Krnjaic and McDermott, 1905.02727

- Predictions can be tested in laboratory.

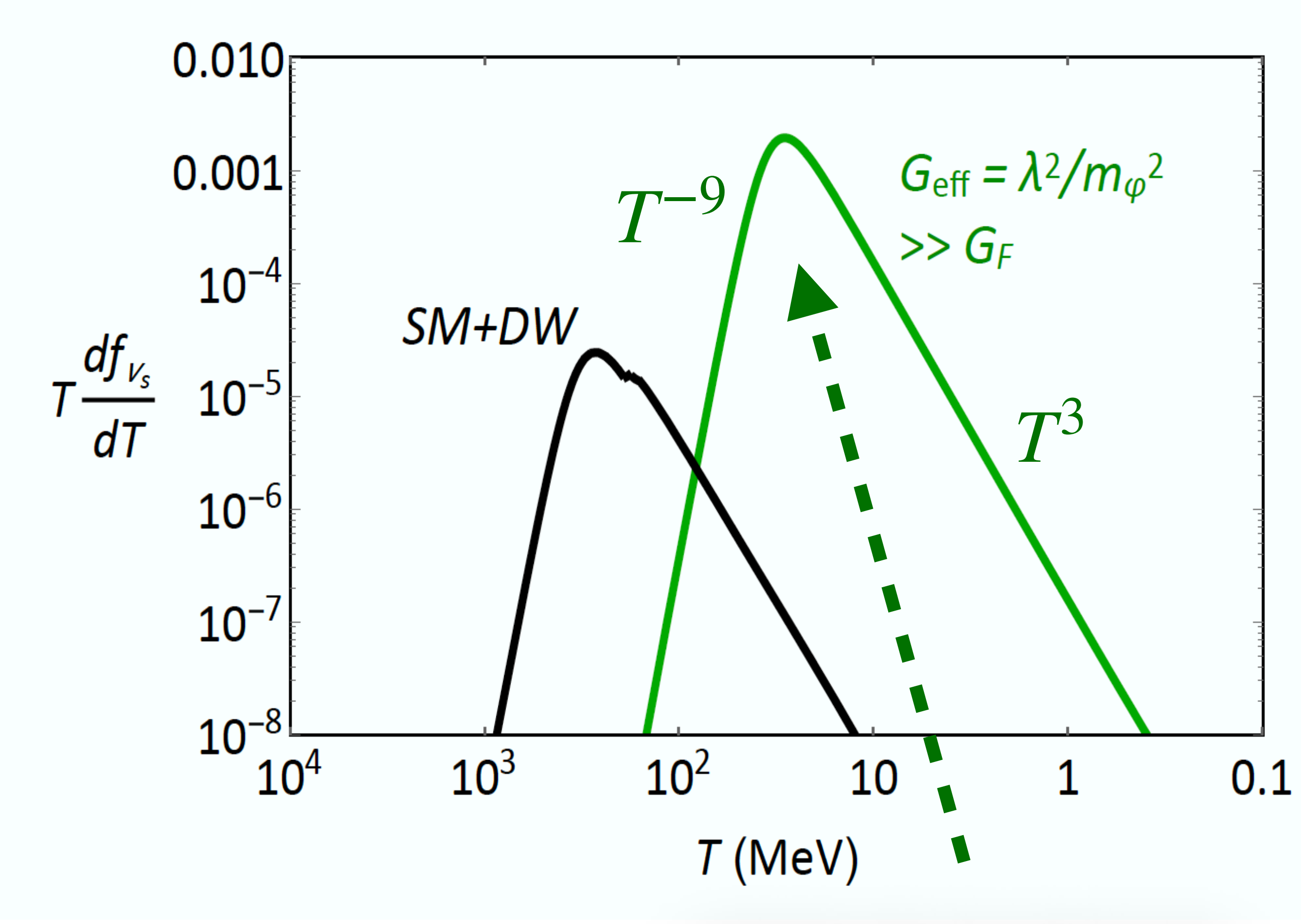
Heavy mediator φ



- Similar to DW, except with a stronger interaction.

$$\Gamma_a \sim \frac{\lambda_\varphi^4}{m_\varphi^4} E T^4, \qquad V \sim -\frac{\lambda_\varphi^2}{m_\varphi^4} E T^4$$

- Integrate around peak-production to obtain $\Omega \propto \frac{\lambda_\varphi^3}{m_\varphi^2} m_4 \sin^2 2\theta$.

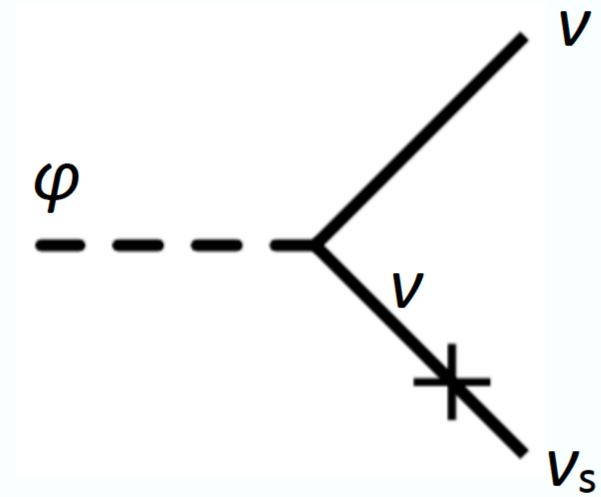


Production peaks at a lower temperature

de Gouvêa, MS, Tangarife and Zhang

Light mediator φ

- If $m_\varphi < T$, then φ can be produced on-shell in the plasma.



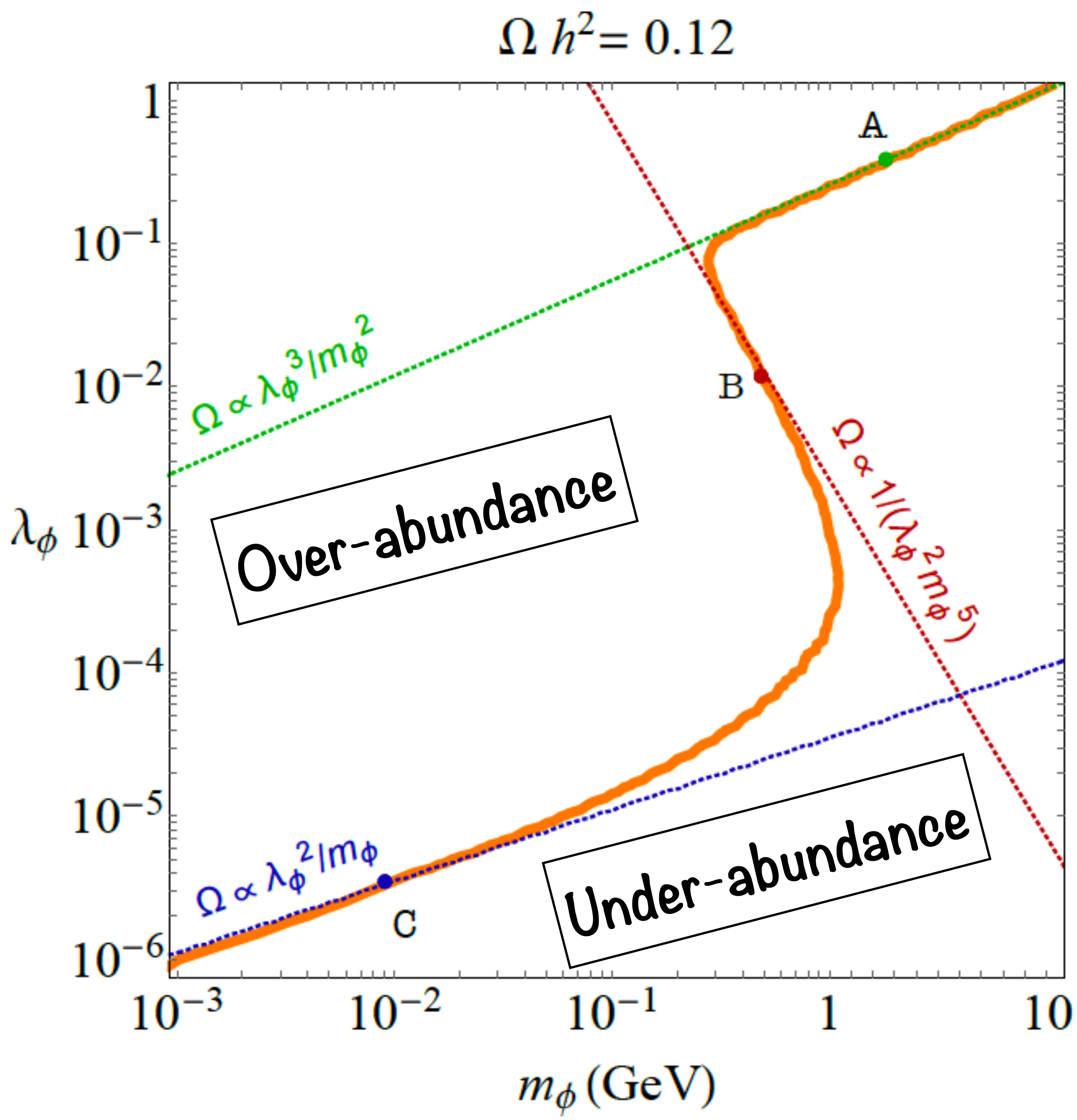
- Now, $\Gamma_a \sim V \sim \dfrac{\lambda_\varphi^2 T^2}{E}$. (Note that V changes sign)

- $\Gamma_a \sim \lambda_\varphi^2$, hence decay is more important than scattering, which goes as λ_φ^4.

- $V > 0$ allows for resonance in

$$\langle P(\nu_a \to \nu_s) \rangle \sim \frac{\Delta^2 sin^2 2\theta}{\Delta^2 sin^2 2\theta + \frac{\Gamma_a^2}{4} + (\Delta cos 2\theta - V)^2}$$

Numerical and analytical estimates

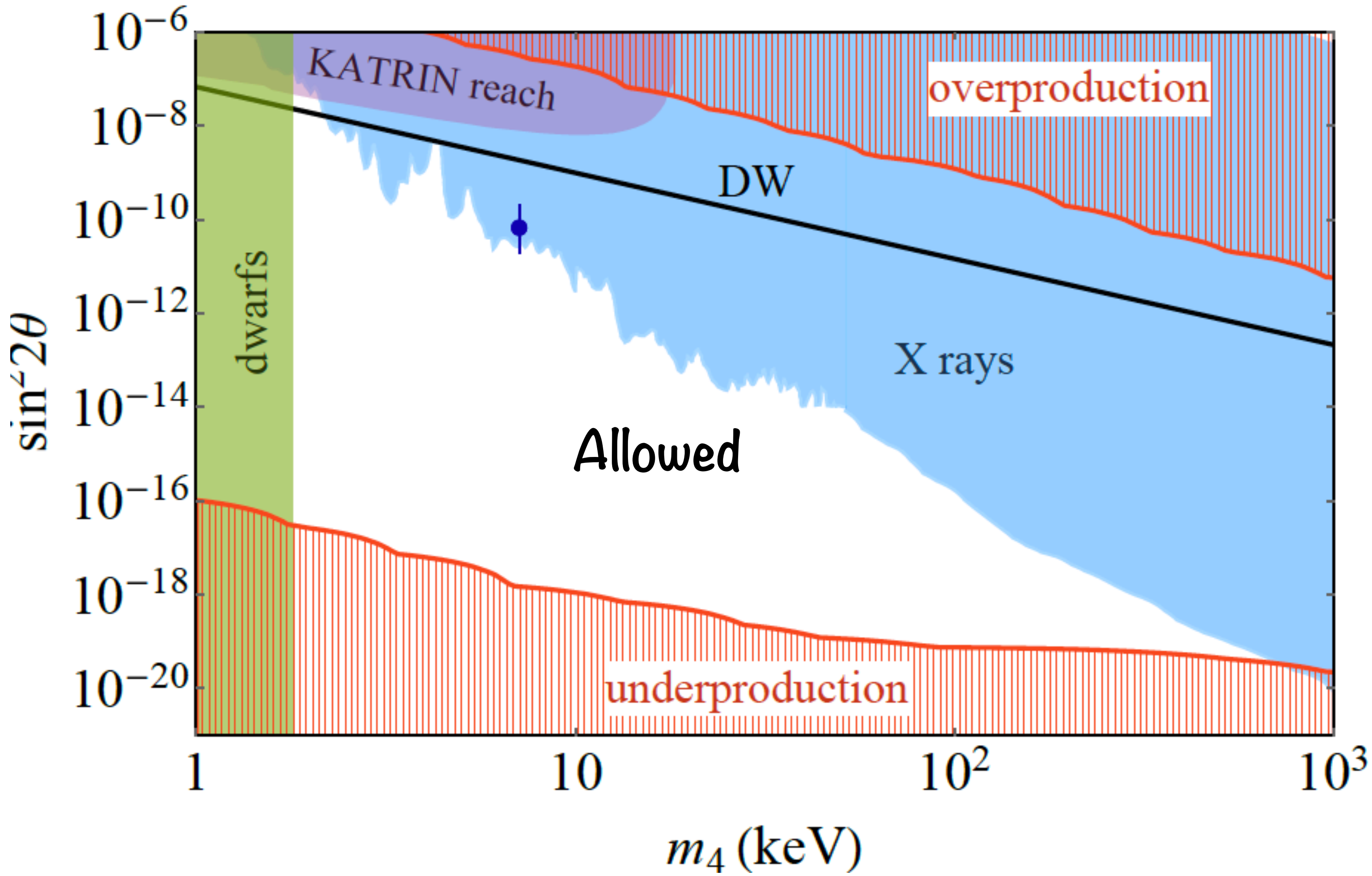


de Gouvêa, MS, Tangarife and Zhang

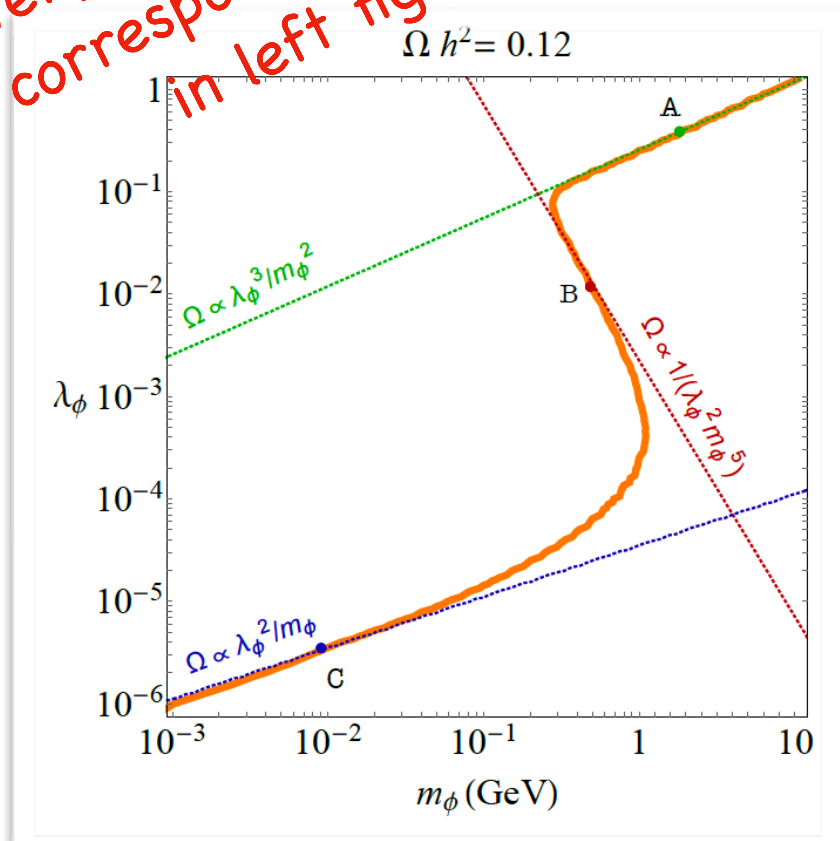
- Allowed parameter space for $m_{\nu_s} = 7.1\,\mathrm{keV},\ \sin^2 2\theta = 7 \times 10^{-11}$
- Analytical estimates:

1. Green: heavy φ
2. Red: light φ, also λ_φ not tiny, hence θ not suppressed. Peak production never reached.
3. Blue: light φ, also λ_φ tiny. $\theta_{\mathrm{mat}} \sim \theta_{\mathrm{vac}}$

Allowed Relic Density window



Every point in this plane corresponds to a point in left figure



de Gouvêa, MS, Tangarife and Zhang

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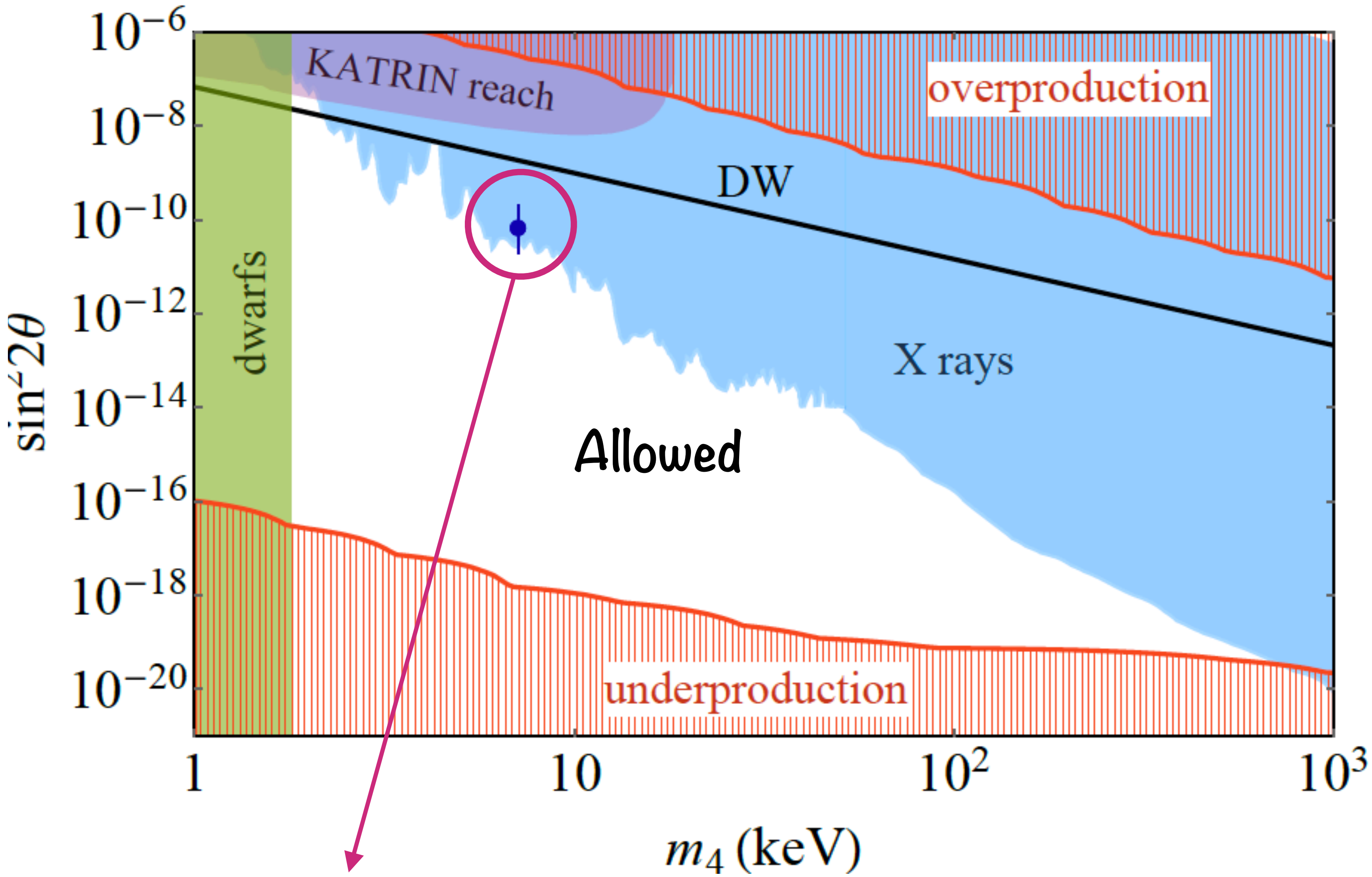

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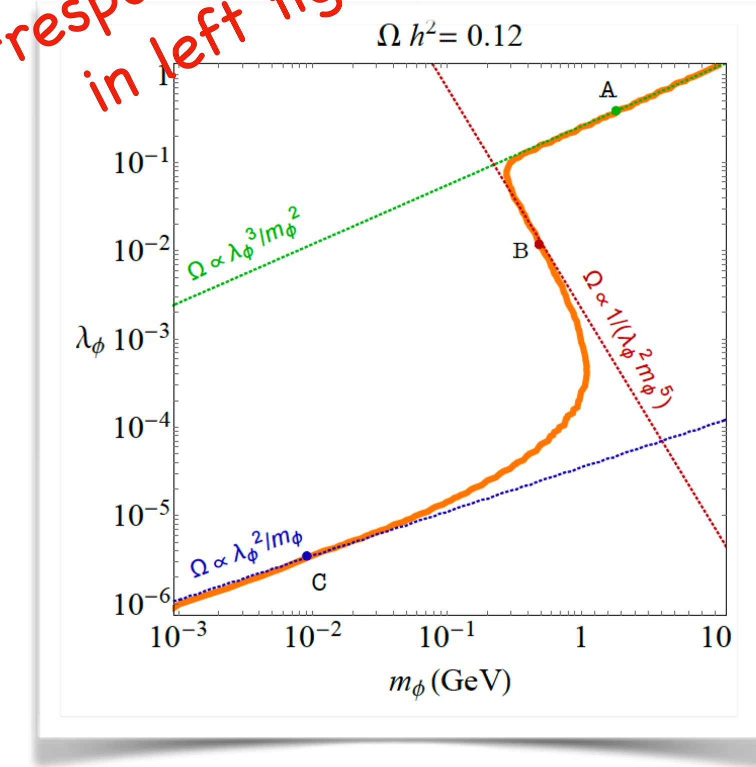
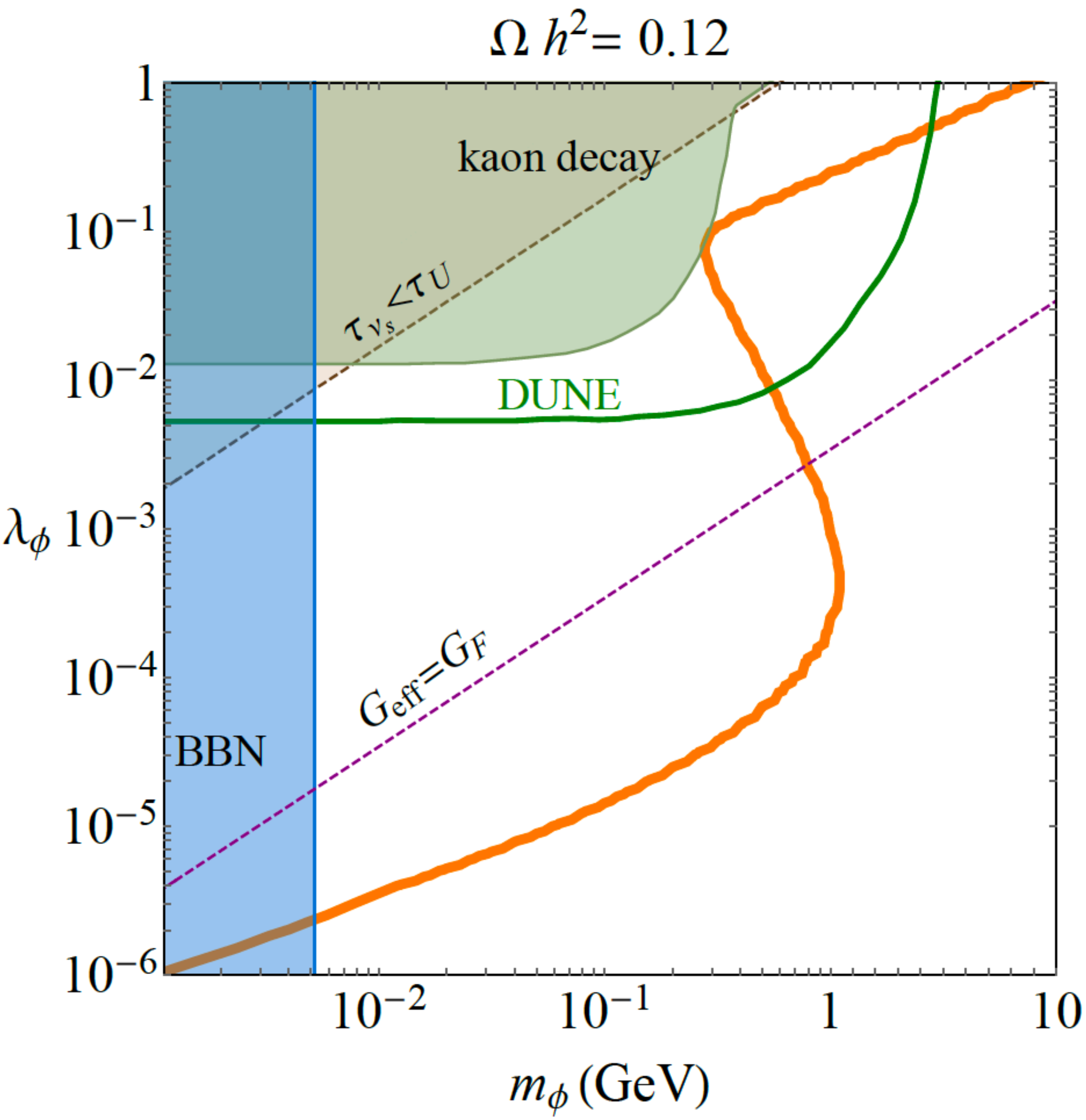


Can be used to satisfy the 3.5 keV X-ray line also ~

$m_{\nu_s} = 7.1\,\mathrm{keV},\ \sin^2 2\theta = 7\times 10^{-11}$ Bulbul et al. Astro. 2014

Experimental tests



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- Interested in range $1\,\mathrm{MeV} \leq m_\varphi \leq 10\,\mathrm{GeV}$
- $K^- \to \mu^- \nu_\mu \varphi, \quad \varphi \to \nu\nu\,.$ Bounds from $\mathrm{Br}(K^- \to \mu^- 3\nu) < 10^{-6}\,.$
- BBN bounds on m_φ.
- DUNE can look for "wrong sign muon" in $\nu_\mu N \to \mu^+ N' \varphi$.

Berryman, de Gouvêa, Kelly and Zhang PRD2018
Blinov, Kelly, Krnjaic and McDermott, 1905.02727
Kelly and Zhang PRD 2019

Summary

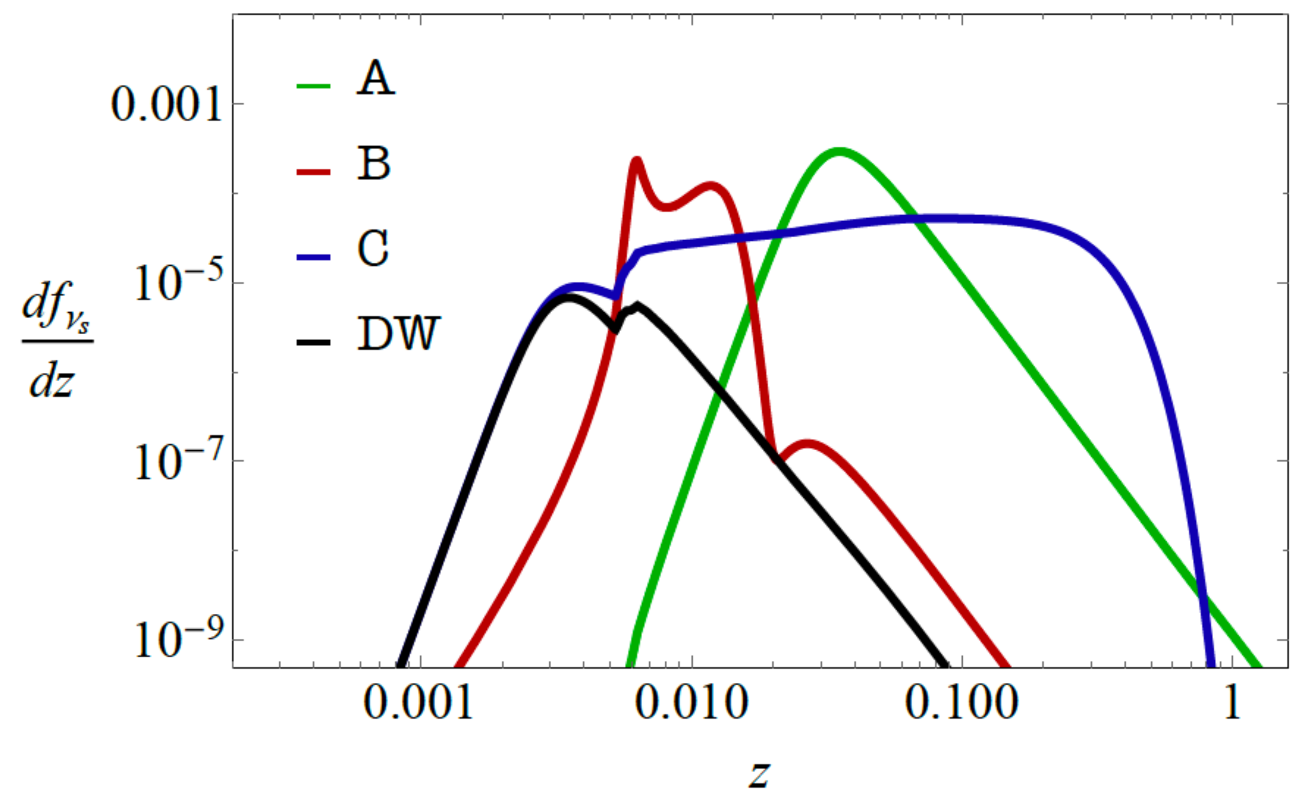
- The SM appended with sterile neutrinos, and a new scalar, which mediates active neutrino self-interactions, much stronger than weak interactions.

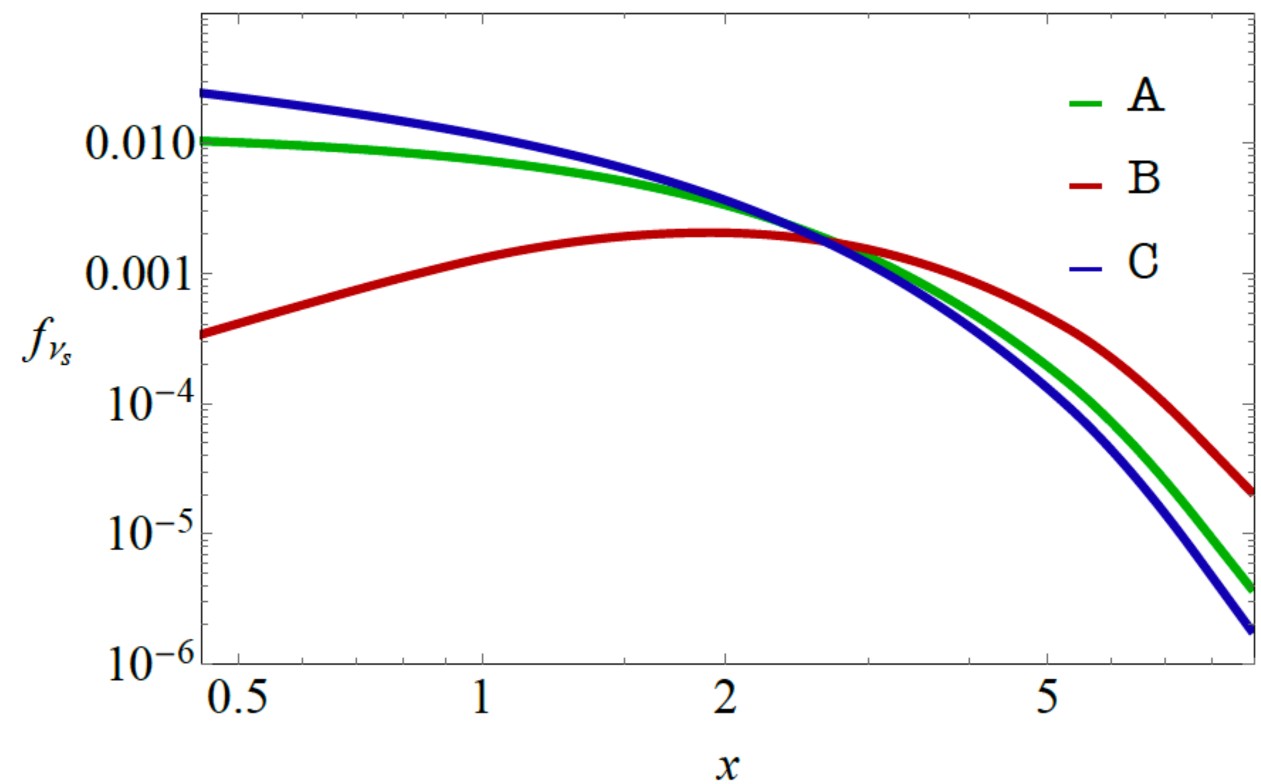
- Sterile neutrinos can be produced non-thermally via freeze-in, using new interactions. Stronger interactions helps alleviate tensions with DW mechanism. Also a possible candidate for the 3.5 keV line.

- Can be probed using upcoming neutrino experiments like DUNE.

THANK YOU!

Backup


A
B
C
DW
0.001
10^{-5}
10^{-7}
10^{-9}
$\frac{df_{\nu_s}}{dz}$
0.001
0.010
0.100
1
z


A
B
C
0.010
0.001
10^{-4}
10^{-5}
10^{-6}
f_{ν_s}
0.5
1
2
5
x